

EVALUATION OF ENERGY STORAGE POSITIONS IN A LOW-VOLTAGE DISTRIBUTION FEEDER USING DIRECT COMPUTER MODELLING

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ABSTRACT

Energy can be considered one of the most important assets of modern society. It is essential for our community's functionality and sustainability. Yet with a continuous growth in population and therefore energy demand, the task of keeping the demand and supply of energy balanced becomes more difficult. With current fossil fuelled power stations, it is possible to compensate for increasing and decreasing energy demand, yet it is beneficial and economical not having to do so. One improvement would be if the fluctuating energy demand was smoothened and thus became more predictable. A way to do so is to implement energy storage. Modelling a distribution feeder to determine more beneficiary locations for energy storage as well as proving the concept of direct computer modelling was addressed in this research project and is summarised in this paper.

1. INTRODUCTION

This project aimed to create a framework that allowed the simulation and evaluation of portions of an electricity grid using a novel approach called direct computer modelling. Using this framework it was targeted to determine whether there is a distinctively beneficial position for energy storage along a low-voltage distribution feeder.

1.1. The Grid

Besides having to transport energy from its generation to the consumption or demand side of the energy grid, the grid also needs to balance them both. This is due to the fact that energy can only be consumed when it is generated, making the balancing of demand and supply very important. Nowadays with fossil fuelled power plants, correcting for such imbalance is relatively easy, yet this demands stations to remain in an idle state without contributing to the grid. Being in such a state creates additional costs and make electricity more expensive than it needs to be.

This problem can be overcome by for instance smoothening the energy demand to such extend that it becomes easier to predict future demand. In an ideal scenario a linear and continuous energy demand would

result where no additional correction would be needed. A possible way improving the demand fluctuation is to implement energy storage.

The benefits of energy storage are known [1]. Since modern storage solutions have grown to become a rather complex, deciding upon correct technology and configuration is very important. Yet choosing the correct location for energy storage can probably be considered the most important decision. This is because correcting for false placement is difficult and costly.

For simplification, one can divide the electricity grid into four categories: generation, transportation, distribution and consumption. Since the problem causing for balancing is located at the consumption side, placing energy storage the furthest away from generation would benefit the majority of the grid.

Positioning and evaluating the location of a storage solution in the low-voltage distribution feeders of such an electricity grid was therefore the main research of this project. Implementing storage at the end of the feeder suggests advantages of low size, cost and additive, distributed impact. This research thus put particular emphasis on reducing the maximum voltage fluctuation along the feeder and the impact storage location has on this voltage fluctuation.

1.2. Matrix Solving Approach

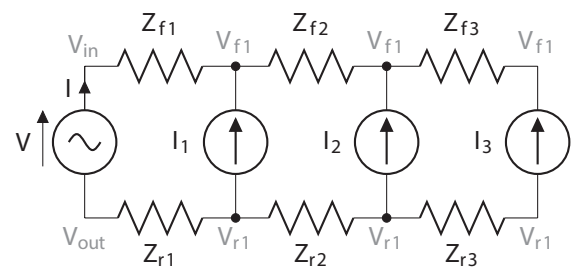


Figure 1 Simple Distribution Circuit

The circuit in Figure 1 illustrates a simplified distribution feeder. Here the voltage source represents the substation to which the feeder (Z_{f1} , Z_{f2} , Z_{f3}) and the return line (Z_{r1} , Z_{r2} , Z_{r3}) are connected. In between feeder and return line lie the clients denoted as current sources (I_1 , I_2 , I_3). This is due to simplification and them being feed with power profiles, making their currents depend upon the adjacent voltage levels. One can formulate an equation for arithmetic solving of the schematics. The result would be the following equation:

$$GV = A \quad (1)$$

$$G = \begin{bmatrix} \frac{Z_{r1} - Z_{r2}}{Z_{r1} Z_{r2}} & \frac{Z_{f1} - Z_{f2}}{Z_{f1} Z_{f2}} & \frac{-1}{Z_{r2}} & \frac{-1}{Z_{f2}} & 0 & 0 \\ \frac{1}{Z_{r2}} & \frac{1}{Z_{f2}} & \frac{Z_{r2} - Z_{r3}}{Z_{r2} Z_{r3}} & \frac{Z_{f2} - Z_{f3}}{Z_{f2} Z_{f3}} & \frac{-1}{Z_{r3}} & \frac{-1}{Z_{f3}} \\ 0 & 0 & \frac{1}{Z_{r3}} & \frac{1}{Z_{f3}} & \frac{(-1)}{Z_{r3}} & \frac{(-1)}{Z_{f3}} \end{bmatrix}$$

$$V = [V_{r1} \ V_{f1} \ V_{r2} \ V_{f2} \ V_{r3} \ V_{f3}]^T$$

$$A = \begin{bmatrix} 2 \left(\frac{P_1}{V_{r2} - V_{f1}} \right) - \frac{V_{out}}{Z_{r1}} - \frac{V_{in}}{Z_{f1}} \\ s \left(\frac{P_2}{V_{r2} - V_{f2}} \right) \\ 2 \left(\frac{P_3}{V_{r3} - V_{f3}} \right) \end{bmatrix}$$

Here, the currents I_1 to I_3 were replaced by their power and voltage changes, since power is known due to recorded power profiles. Normally one would now equate for V to find the voltages along feeder and return line like so:

$$V = G^{-1}A \quad (2)$$

Yet A as well as V contain the feeder and return line voltages which makes it very difficult to solve. Common approaches to solve this equation would be by applying Newton-Raphson [2,3,4], partial differential equations (PDE) [5] or other methods.

1.3. Direct Computer Modelling

The solving approach used here is though a less arithmetic and less abstract one called Direct Computer Modelling [6,7,8]. Instead of implementing an additional layer of abstraction the circuitry is directly modelled into code. This is done through implementing basic elements that communicate with adjacent elements through common ports. The circuit's complexity is reached by matching the number of implemented elements to the number of components described in the circuit. Here, it is the elements' task to follow the basic yet fundamental laws of physics, which allows this natural and easy implementation. With modern object orientated programming languages it is possible to construct one base class which details this fundamental element functionality and behaviour. More complex elements can be constructed upon this class. By executing all these elements across a network of parallel processes with access to a global solving plane, the computation time is drastically decreased. This is due to the intrinsic parallelism captured in the Direct Computer Modelling formalism.

Before outlining the results found through the research and concluding, the procedures and model implementation are outlined in the method section.

2. METHOD

Since the Direct Computer Modelling methodology is designed to be implemented in a highly parallel manner and due to the lack of computational resources, a more

sequential alternative had to be developed. Its functionality and how it was implemented is detailed in the following section.

2.1. Algorithm

The algorithm constructed utilised the complexity of the households (previously represented as current sources) and modelled them as loop-breaking elements. Instead of forwarding the current and voltage information, they would simply return a requested parameter (i.e. impedance) whose value had to be computed depending upon the element's port voltages. Doing so, a procedural computation became possible since infinite iteration loops (due to loop currents) are avoided.

For a sequential execution of a feeder problem, an entry point had to be chosen. The best place would be at ends of the feeder where the voltage values remain constant.

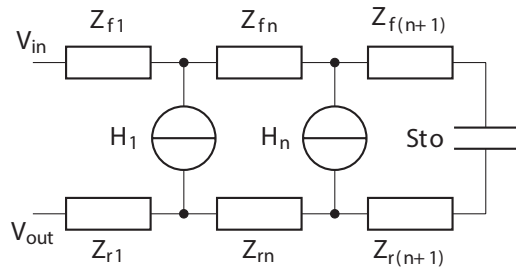


Figure 2 Direct Computer Modelling Schematic

Following Figure 2 these points would be at V_{in} and V_{out} . In order to solve for the total current flow, the system would call the neighbouring element's total impedance (here Z_{f1}). This element in turn would then call its neighbouring elements' impedances and add them to its own impedance before returning the circuit's total impedance. It is worth noting that in the case where multiple elements return parameters to the same originating element, they are not simply added but follow the product over sum rule for parallel impedances. Once the first current has been found the algorithm chooses the next element (here Z_{fn}) solves for its current until the last element has been reached.

The Sto element was implemented in the Figure 2 to take the place of energy storage and was only used in evaluative cases – that was when storage location was evaluated. Otherwise one can consider it as an open circuit or even remove it completely to simplify the computation.

Once all feeder currents have been computed, the algorithm would start the same iterating process from the V_{out} along the return line and update its currents. It is only now when the H_1 to H_n elements start refreshing their port voltages, which were used to compute the returned impedances. This way future enhancement to multiple phases would become possible, since each feeding phase could be treated separately until the return line is updated. For further convenience a feeder-house-return block can be treated as one branch. These can then

easily be appended to form longer chains for quick implementation and alternation.

2.2. Implementation

As the main task of this project laid on determining beneficiary energy storage locations, the algorithm was embedded in a framework, which allowed positioning the energy storage *Sto* at different locations along the feeder branch. When for instance appending it to the end of the branches, it needed to be separated by two additional impedances denoted as $Z_{r(n+1)}$ and $Z_{r(n+1)}$. For the case where storage was inserted in between two clients, say H_l and H_n , the impedances Z_{fn} and Z_{rn} needed to be halved. Implementing this dynamically at block construction removed the need to alter impedances after a storage position had been selected.

Having established this basic framework that allowed quick setup, the framework needed to simulate the circuitry. Using a provided dataset containing power profiles of 542 anonymous Irish households covering 154 days at a 30 minutes sampling rate allowed running simulations as close to reality as possible.

Being capable of executing one static simulation for a given household combination, analysis still needed to take place. Stochastic analysis was used to evaluate the output data, where each branch was treated separately. Here, the maximum and minimum potentials across the clients were extracted, recoded and sorted before a Gaussian frequency distribution for each branch was plotted. To allow better comparison box-plots were used instead of the actual bell curves.

After having executed multiple static non-evaluative simulations (say 48) a storage profile was generated. It was based upon a common node control where the node was the branch potential located the furthest from the substation. This was done due to the maximum voltage drop being recoded there, thus making the impact most visible and interpretable. The triggering value chosen was the median. This would also balance the storage's energy input and output. For evaluative simulations where storage is no longer an open circuit, this power profile was then be fed into the *Sto* element, parallel to the original clients' power profiles. Although this way of generating a storage profile is very simplistic, it is

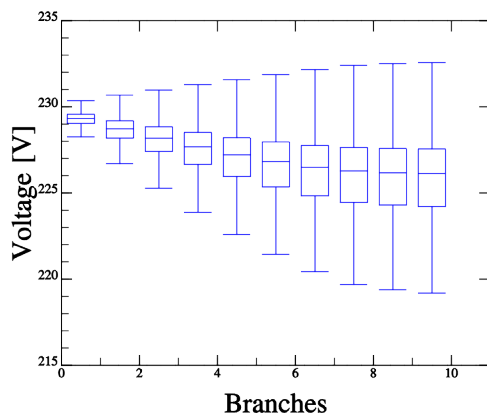


Figure 4 Branch data analysis without storage

noteworthy that focus was put on the location of energy storage and its impact, not its realism.

The framework was therefore capable of solving one static problem. To make it dynamic a long dataset was applied. With multiple results generated from multiple executions, an energy storage profile could be extracted, which in turn as feed into the next set of iteration where the storage location is evaluated. Here, for a feeder of n branches in length, $n+1$ numbers of positions had to be evaluated. E.g. to evaluate a ten branches long feeder, one reference and eleven analysis simulations need to be executed. After successful execution the same analysis procedure used for the reference was applied allowing good comparison.

For speedier computation, the entire simulation was run on the campus grid (comprising of 170 clients) where multiple jobs could execute in parallel. Still the total execution time was estimated to be around 34 days.

3. RESULTS

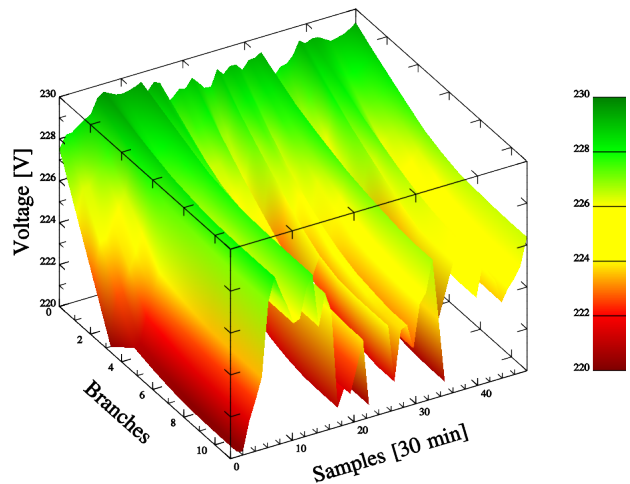


Figure 3 Feeder voltage drops against time

Figure 3 represents the voltage drops of individual feeders (*along branches*) over a sampling period of one day with a sampling interval of 30 minutes. Although this excerpt of the whole 154 days illustrates the change and extent of voltage drop over time, it does not allow good analysis.

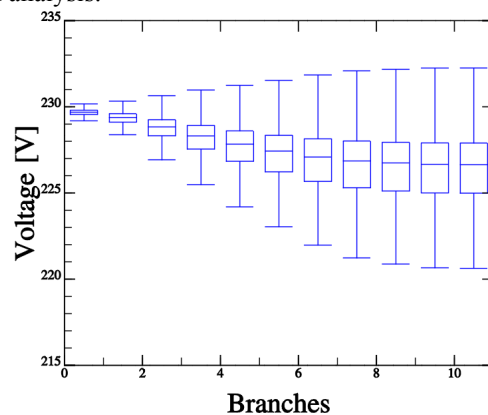


Figure 5 Branch data analysis with storage

Figure 4 statistically represents the complete data set with storage disconnected (hence a missing 11th branch). This is used as a reference for performance analysis.

Figure 5 represents the same setup but with implemented and storage profile fed energy storage at position 11. The inter-quartile range has noticeably reduces in comparison to before.

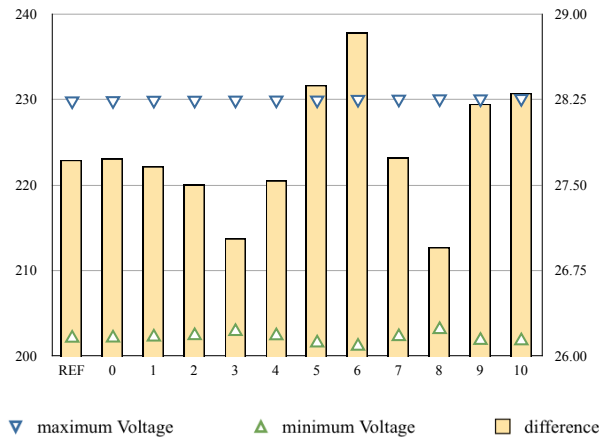


Figure 6 Final result

In Figure 6, the final analysis of all executions is captured. It must be noted that the maximum and minimum voltages are not branch dependent, but are taken from the entire feeder for one chosen storage placement. Furthermore, Figure 6's left axis relates to the maximum and minimum voltages whilst the right axis scales the difference between the two.

4. CONCLUSION

Through comparison and referencing results with other means as well as checking the returned values by hand, one can find the Direct Computer Modelling paradigm to have worked successfully. From the data generated and recorded in stochastic analysis graphs, one can see that the computed storage profile did indeed improve the specific scenario. When focusing on the absolute maximum and minimum values, which are of interest to the network operators, placing energy storage at the first or last quarter of the feeder seems to be the solution with most benefitting impact.

The metric of success shown was used since network operators must not break standardised specifications that regulate the maximum voltage fluctuation along the feeder. To avoid expenses caused by low supply voltages, operators have the possibility to increase the supply voltage by 10% from 230V.

Cases that cause inverse current flows or where the energy storage solution has been placed away from the problem area (e.g. a client drawing a lot of power), can mitigate the impact and even worsen the scenario. This statement is supported by the increased potential difference when locating the storage solution in the middle of the feeder.

Although this analysis is very informative, it also is very potential focused and does not accommodate for current fluctuation. Nevertheless it is high currents causing additional thermal losses, especially alternating currents due to unwanted complex losses. Future research may include this to determine a voltage as well as current weighted solution.

Acknowledgement: I would like to thank Dr B. Potter for the guidance and technical support as well as for supervising this project.

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